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RAPIDLY STAR-FORMING GALAXIES AT HIGH REDSHIFTS

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Abstract. *Herschel* has opened new windows into studying the evolution of rapidly star-forming galaxies out to high redshifts. Today's massive starbursts are characterized by star formation rates (SFRs) of $\sim 100 + M_{\odot}$/yr and display a chaotic morphology and nucleated star formation indicative of a major merger. At $z \sim 2$, galaxies of similar mass and SFR are characterized by ordered rotation and distributed star formation. The emerging cold accretion paradigm provides an intuitive understanding for such differences. In it, halo accretion rates govern the supply of gas into star-forming regions, modulated by strong outflows. The high accretion rates at high-z drive more rapid star formation, while also making disks thicker and clumpier; the clumps are expected to be short-lived in the presence of strong galactic outflows as observed. Hence equivalently rapid star-formers at high redshift are not analogous to local merger-driven starbursts, but rather to local disks with highly enhanced accretion rates.

1 Introduction

Herschel has revolutionized far-infrared studies of the interstellar medium (ISM) in rapidly star-forming galaxies at high redshifts. Recent observations have accurately characterizing the peak of their dust-reprocessed emission, and in some cases even have detected key ISM cooling lines. This has resulted in significantly more robust determinations of galaxy star formation rates and ISM physical conditions, thereby lending crucial insights into the physics of high-z star formation.

A key result known prior to, but whose robustness was greatly increased by, *Herschel* is that the luminosity density in the infrared evolves quite strongly with redshift. For instance, Gruppioni et al. (2010) determined that the IR luminosity density evolves as $(1 + z)^{3.8}$ up to $z = 1$ and continues to increase to earlier epochs, and they attributed this increase to the prevalance of starburst galaxies at early epochs. Yet the increase is reflective of an overall evolution in the galaxy

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population rather than in a particular class of systems: At any given stellar mass, the star formation rate of a galaxy at $z = 2$ is more than an order of magnitude higher than one at $z = 0$ (Nordon et al. 2010). Morphological studies of high-z galaxies generally show a lumpy or chaotic morphology, which if seen in a galaxy today would surely be classified as a merger event. These and related observations are often taken as strong support of a scenario in which merger-induce starbursts are more common at higher redshifts, and become largely responsible for driving galaxy evolution at early epochs. This scenario meshes well with the notion of hierarchical structure formation in which small systems form first and assemble through mergers into larger systems.

In contrast, recent hydrodynamical simulations of cosmological galaxy formation consistently suggest that mergers are sub-dominant in fueling galaxy growth (Murali et al. 2001, Kereš et al. 2005, Guo & White 2008, van de Voort et al. 2010). Instead, these models generically predict that gas feeding primarily occurs through cold, smooth streams (Kereš et al. 2005, Dekel et al. 2009, Kereš et al. 2009), and while those streams also carry in galaxies, major mergers that would induce strong starbursts are rare. This so-called "cold accretion" is predicted to be particularly strong at early times when cosmic star formation peaks, and so is expected to drive galaxy growth in the epoch now being probed by *Herschel* and other telescopes. The natural question then arises, are the properties of high-z galaxies now being detected in accord with expectations from this scenario? In particular, how does one explain the rapid increase with redshift in star formation rates and disturbed morphologies within the cold accretion paradigm?

2 Gas Fueling

Far from galaxies, the motion of baryons is largely governed by the mass-dominant dark matter. To a reasonable approximation, the accretion rate of baryons into halos is then expected to be given by the accretion rate of dark matter times the cosmic baryon fraction. Simulations confirm this, and have shown that it is largely insensitive to feedback processes (van de Voort et al. 2010).

The accretion rate onto dark matter halos can be accurately characterized as a function of mass and redshift assuming a currently-favored ΛCDM cosmology. Neistein et al. (2006) computed halo accretion rates both from analytic Press-Schecter based arguments as well as from dark matter (i.e. N-body) simulations, and showed that the baryon halo accretion rate is well-described by

$$\dot{M}_{\rm in} = 6.6 M_{12}^{1.15} (1+z)^{2.25} f_{0.165}\ M_\odot {\rm yr}^{-1} \tag{2.1}$$

where M_{12} is the halo mass in units of $10^{12} M_\odot$, and $f_{0.165}$ is the cosmic baryon fraction in units of the WMAP-concordant value $f_b = 0.165$ (Dekel et al. 2009).

This equation implies that at $z = 0$, a Milky Way-sized galaxy's halo ($10^{12} M_\odot$) will accrete $\sim 7 M_\odot$/yr of gas into its virial radius. The star formation rate in the Milky Way is $\sim 1 - 3 M_\odot$/yr (see Robitaille & Whitney 2010 and references therein), indicating that, as one might expect, only some of the accretion into

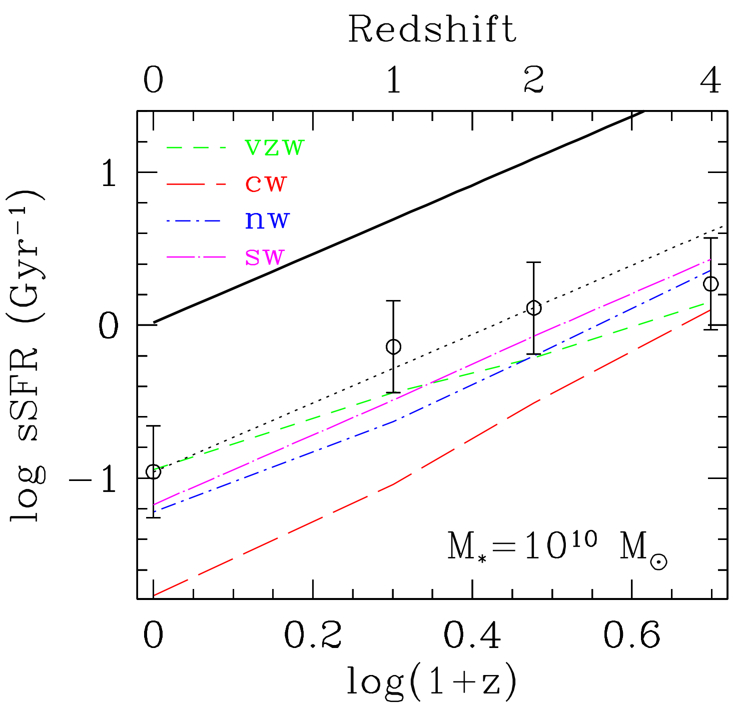

Fig. 1. Comparison of models to data for the evolution of the sSFR of a galaxy with $10^{10} M_\odot$ of stars. Observations, shown as the circles with an approximate 1σ spread of ± 0.3 dex, are shown at $z = 0, 1$ (Elbaz et al. 2007) at $z = 2$ (Daddi et al. 2007) corrected downwards by a factor of 1.5 as suggested by *Herschel* data (Nordon et al. 2010), and at $z = 4$ from Stark et al. (2010). The model lines of various colours/line types show results from cosmological hydrodynamic simulations (Davé et al. 2011), with various prescriptions for galactic outflows, including a model without outflows (nw). The thick solid line shows the prediction from equation 2.1 assuming a halo mass of $2 \times 10^{11} M_\odot$, while the dotted line shows a similar redshift scaling normalized to the observed $z = 0$ sSFR.

the halo's virial radius actually forms into stars. We will argue in §3 that this is indicative of ejective feedback, but for now let us focus on the redshift evolution.

A similar-sized halo at $z = 2$ will, by equation 2.1, accrete at $\approx 80 M_\odot$/yr. Under the simple assumption that a constant fraction of halo accretion ends up forming into stars, it is immediately seen that the star formation rate of a given mass galaxy at $z = 2$ should be more than an order of magnitude higher than at $z = 0$. The observed evolution of the specific star formation rate (sSFR) is indeed consistent with such an increase out to $z \sim 2$ (Noeske et al. 2007, Daddi et al. 2007)

Hydrodynamic simulations that attempt to directly model the growth of galaxies are also consistent with this scenario. Figure 2 shows the evolution of the sSFR as a function of $\log(1 + z)$, comparing expectations from the cold accretion

paradigm, predictions from hydrodynamic simulations, and observations. The thick solid line shows the power-law relation from equation 2.1, and the dotted line shows a similar scaling assuming a constant fraction of star formation relative to halo accretion, normalized to the observed $z = 0$ data. Observations are shown as the circles, scaled to a fiducial stellar mass of $10^{10} M_\odot$ (see Davé et al. 2011). In general, the observed evolution of the sSFR nicely follows equation 2.1. Also shown are results from cosmological hydrodynamic simulations (Oppenheimer et al. 2010,Davé et al. 2011) with various prescriptions for galactic outflows. In each case, the evolutionary trend broadly follows that expected for cold accretion. The trend itself is relatively insensitive to feedback prescription (Davé 2008, Dutton et al. 2010), but the overall amplitude can be affected in extreme feedback models.

Hence the cold accretion paradigm naturally explains the overall reduction in cosmic star formation rates at a given mass as a direct consequence of dropping hierarchical mass accretion rates. The key implication for understanding galaxy evolution is that galaxies with an order of magnitude higher SFRs at high-z should not be seen as analogs of local starbursts, but rather analogs of local disks being smoothly fed at much higher accretion rates. Just because $z \sim 2$ galaxies have high star formation rates does not make them starbursts; they are simply processing gas as supplied, and hence are "supply-limited" just as local disks today. The gas supply can be strongly tempered by feedback as we discuss next, but the simple ansatz of a roughly constant fraction of the virial radius accretion forming into stars broadly matches observations.

3 The Role of Feedback

In simulations without galactic outflows, the accretion rate onto a galaxy is only slightly smaller than that at its virial radius (Kereš et al. 2009, van de Voort et al. 2010, Ceverino et al. 2010) in cold accretion-dominated halos (i.e. $M_{\rm halo} <\sim 10^{12} M_\odot$). This is because cold streams operate to efficiently channel gas down filaments connecting to large scale structure, and the enhanced density within the filaments prevents the formation of an accretion shock along its path. It is therefore difficult to stop rapid accretion onto a galaxy unless the halo is sufficiently large so as to disrupt the cold streams, and perhaps not even then (Kereš & Hernquist 2009).

If most of the gas accreting into the virial radius reaches near the disk, one would expect in a steady-state situation that the star formation rate would be comparable to the accretion rate. This contradicts observations of, e.g., the Milky Way, where the SFR is only a fraction of the accretion rate. Furthermore, the baryon fraction in stars relative to the overall baryon fraction expected in halos is small, in fact peaking around Milky Way-sized objects at $\sim 25\%$ and dropping off to either higher or lower masses (McGaugh et al. 2010, Dai et al. 2010). Hence something must be preventing that accreted gas from forming into stars. Given that galaxy gas fractions are seen to be dropping with time (Tacconi et al. 2010), the gas cannot be piling up in the disk unused (barring it being in some hidden form, which appears unlikely). Hence an inevitable conclusion of the cold accretion

paradigm is that galactic outflows, i.e. kinetic removal of gas from the star-forming regions, must be prevalent.

Observations are amassing that outflows are ubiquitous in high-redshift galaxies (e.g. Steidel et al. 2004, Weiner et al. 2009, Steidel et al. 2010). Such outflows have also been invoked in models to enrich the intergalactic medium (e.g. Oppenheimer & Davé 2006) and modulate the growth of stellar mass (e.g. Oppenheimer et al. 2010, Davé et al. 2011) and metallicity (e.g. Finlator & Davé 2008). Perhaps the most surprising aspect of these models is that the amount of material ejected must significantly exceed the amount forming into stars (Oppenheimer & Davé 2008). In the cold accretion paradigm, this makes sense because the star formation rates are a small fraction of the accretion rates, and hence the rest must be ejected.

Overall, cold accretion must work together with outflows if this paradigm is to yield galaxies as observed. To zeroeth order, there is a simple balance between gas accretion at the virial radius supplying gas, and star formation and outflows removing gas from the ISM. The evolution of this equilibrium then governs the observable properties of galaxies across cosmic time (Davé et al. 2011). In detail, the amount of accretion onto galaxies does depend on feedback processes, even in the low-mass regime dominated by cold accretion (van de Voort et al. 2010). Furthermore, winds often recycle back into galaxies, providing another accretion path that may be dominant at late epochs (Oppenheimer et al. 2010). Nevertheless, this simple scenario is at least broadly consistent with available data, and can help to place the observed evolution of galaxies out to high redshifts within a hierarchical context.

4 Morphology and Kinematics

The morphology and kinematics of high-z galaxies have drawn considerable attention, particularly with the emergence of near-infrared integral field units on large telescopes such as SINFONI and OSIRIS. The SINS survey (Förster Schreiber et al. 2009) has revealed the particularly interesting trend that higher-mass galaxies at $z \sim 2$ tend to show more ordered rotation, despite having clumpy and irregular Hα maps that suggest ongoing interactions (Genzel et al. 2006). It is possible that the apparent rotation could actually be two merging similar-mass galaxies in orbit (Robertson & Bullock 2008), but the prevalance of rotation signatures together with the expected rarity of major mergers caught exactly at such a stage means that such an explanation is unlikely for most of these objects.

Reconciling the clumpy morphology and ordered kinematics of $z \sim 2$ galaxies has provoked a number of simulators to re-examine disk galaxy formation tailored to high redshifts. Bournaud et al. (2008) showed that a disk evolving in isolation under conditions as observed at high-z would fragment quickly, producing a clumpy morphology with ordered kinematics as observed. This requires that the initial bulge component be small, which Bournaud & Elmegreen (2009) argued cannot be the case if mergers (which are believed to grow bulges) dominate early galaxy growth. The clumps form from self-gravitational instabilities within the disk, without associated dark matter halos, and can migrate inwards to grow a

bulge secularly (Ceverino et al. 2010). Bournaud et al. (2010) showed using AMR hydrodynamic simulations gravity-driven turbulence feedback can produce thick disks with substantial velocity dispersion, in agreement with observations. Hence overall, the secular formation of clumpy disks seems to be at least plausible given the conditions (particularly the high gas fractions) of high-z galaxies.

However, the issue of clump growth and migration has elicited some concerns. If the clumps are long-lived and sink to the middle, and are a ubiquitous feature of high-z galaxies, then it becomes difficult to explain the formation of late-type galaxies today; this is the longstanding angular momentum problem (e.g. Steinmetz & Navarro 1999). Furthermore, we argued earlier that the SFR cannot be comparable to the accretion rate over long timescales, as happens in these models (e.g. Ceverino et al. 2010), since this would significantly overproduce the fraction of baryons in stars (i.e. the longstanding overcooling problem). Indeed, the fragmentation of disks in models without significant ISM feedback is a well-known result that has generally been regarded as a catastrophic failure by those aiming to simulate present-day disks (e.g. Robertson et al. 2004). Hence either the clumpy disk interpretation of the observations is flawed, or else some physical ingredient is missing in these models.

The missing ingredient is likely to be galactic outflows. Genel et al. (2011) studied the formation of a high-z disk galaxy including outflows. The model for outflows was heuristic and parameterized, but it followed an outflow model demonstrated to broadly match a range of galaxy and intergalactic medium properties. The key new finding is that while marginally-stable clumps form as found by others, the mass loss owing to strong outflows enables clump disruption on short timescales, well before they are able to sink to the middle and grow a bulge. Their resulting galaxy showed a significantly smaller fraction of baryons in stars, in better accord with data. The properties of these simulated clumps are in good agreement with SINFONI observations of individual clumps by Genzel et al. (2011), which also show strong outflows with mass loss rates significantly exceeding their SFR, and modest turbulence likely driven mostly by gravity.

The implications for disrupting clumps are numerous and, in general, favorable towards forming disk galaxies as observed. In particular, it has long been suggested that the angular momentum problem may be solved if outflows preferentially remove low angular momentum gas. The specific angular momentum distributions within dwarf galaxies today show a marked deficit of low angular momentum gas relative to expectations from a simple disk collapse model (van den Bosch et al. 2001). Indeed, Governato et al. (2009) was able to form a bulgeless dwarf galaxy by including strong feedback which they argued removed the low angular momentum gas, although it remains to be seen if the same mechanism can operate in a larger galaxy. The disruption of clumps by outflows suggests a slight modification to the canonical interpretation: It is not that low angular momentum gas is preferentially removed, but rather that gas is expelled from clumps before it would have otherwise lost its angular momentum and grown the bulge. This alleviates the need for outflows to originate near the centers of growing galaxies, and can instead be driven from where star formation is occuring.

5 Summary

The evolution of star-forming galaxies from $z \sim 2 \rightarrow 0$ has yielded several paradoxical results in terms of the importance of mergers in driving their evolution. The disturbed morphologies and high star formation rates at $z \sim 2$ are often analogised with mergers seen today. Conversely, the kinematics show ordered rotation, and detailed analyses of lensed galaxies' infrared SED suggest that they are more similar to local quiescent disks than starbursts (Rex et al. 2010), disfavoring the merger hypothesis.

The seemingly conflicting results can be reconciled within the cold accretion paradigm for galaxy growth. The high star formation rates owe to increased accretion rates at high-z, which result in secular morphological features such as clumps that are not seen in local disks. Most of these systems are not therefore undergoing major mergers; at $z \sim 2$, such mergers probably give rise to the brightest sub-millimeter galaxies, i.e. hyper-LIRGs rather than ULIRGs.

Because it is difficult to prevent dense filamentary cold streams from reaching the disk, the cold accretion scenario must necessarily be accompanied by a mechanism to remove a substantial amount of gas from the star-forming regions, such as galactic outflows. This is motivated by observations that star formation rates are substantially smaller than halo accretion rates in a ΛCDM universe, and that the fraction of baryons forming into stars within halos is small. Outflows can also have significant impact on the internal structure of high-z galaxies, including causing more rapid disruption of clumps and preventing the ubiquitous formation of large bulges. Interestingly, both simulations and observations seem to suggest that the turbulence of high-z disks is *not* a result of feedback but rather is powered by gravitational potential energy, suggesting that outflows escape without depositing much of their energy into their immediate surroundings.

The interplay between accretion, star formation, and outflows remains poorly understood. Simulations are just beginning to explore the connections that span a range of scales from parsecs to megaparsecs. Observations of high-z galaxies are critical for pinning down the key physical processes driving galaxy evolution, and *Herschel* has played, and will continue to play, a central role in that effort.

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